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Altered hydrologic feedback in a warming climate introduces a "warming hole"

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Abstract

In the last 25 years of the 20th century most major land regions experienced a summer warming trend, but the central U.S. cooled by 0.2–0.8 K. In contrast most climate projections using GCMs show warming for all continental interiors including North America. We examined this discrepancy by using a regional climate model and found a circulation-precipitation coupling under enhanced greenhouse gas concentrations that occurs on scales too small for current GCMs to resolve well. Results show a local minimum of warming in the central U.S. (a "warming hole") associated with changes in low-level circulations that lead to replenishment of seasonally depleted soil moisture, thereby increasing late-summer evapotranspiration and suppressing daytime maximum temperatures. These regional-scale feedback processes may partly explain the observed late 20th century temperature trend in the central U.S. and potentially could reduce the magnitude of future greenhouse warming in the region.

Disciplines

Agriculture | Agronomy and Crop Sciences | Atmospheric Sciences | Climate | Environmental Indicators and Impact Assessment | Hydrology

Comments

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[1] In the last 25 years of the 20th century most major land regions experienced a summer warming trend, but the central U.S. cooled by 0.2–0.8 K. In contrast most climate projections using GCMs show warming for all continental interiors including North America. We examined this discrepancy by using a regional climate model and found a circulation-precipitation coupling under enhanced greenhouse gas concentrations that occurs on scales too small for current GCMs to resolve well. Results show a local minimum of warming in the central U.S. (a "warming hole") associated with changes in low-level circulations that lead to replenishment of seasonally depleted soil moisture, thereby increasing late-summer evapotranspiration and suppressing daytime maximum temperatures. These regional-scale feedback processes may partly explain the observed late 20th century temperature trend in the central U.S. and potentially could reduce the magnitude of future greenhouse warming in the region. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1694 Global Change: Instruments and techniques; 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3324 Meteorology and Atmospheric Dynamics: Lightning; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions. **Citation:** Pan, Z., R. W. Arritt, E. S. Takle, W. J. Gutowski Jr., C. J. Anderson, and M. Segal (2004), Altered hydrologic feedback in a warming climate introduces a "warming hole," *Geophys. Res. Lett.*, *31*, L17109, doi:10.1029/2004GL020528.

1. Introduction

[2] Changes in forcing of the climate system can trigger new or altered feedback processes. We have found evidence of such a feedback in the hydrological cycle of the central U.S. that creates a regional minimum within the continental-scale pattern of warming in an enhanced greenhouse-gas climate. The effect of this particular feedback is amplified because a change is introduced into a slowly varying component of the hydrologic cycle (soil moisture) thereby extending the impact of increased summer precipitation to later months in the annual cycle. We investigated these processes using a regional climate model (RCM) to downscale contemporary and future scenario climates from a global climate model (GCM) [*Johns et al.*, 1997] in order to project resolution-enhanced patterns of climate change for the continental U.S. Previous work has shown that the downscaled climate from this approach provides a reasonable representation of the atmosphere-hydrology linkage in this region [*Pan et al.*, 2001a; *Gutowski et al.*, 2003].

[3] The most notable feature in the projected climate is a local minimum of warming (hereinafter called a "warming hole") in the central U.S. during summer (June, July and August) (Figure 1a). The increase in daily maximum surface air temperature (dT_{max}) in summer at the center of the warming hole is less than 0.5 K, which is substantially less than the mean increase of about 3 K over the continental U.S. The ground temperature has an even stronger warming hole with 0.5 K cooling, rather than warming, in the center. The warming hole starts to develop in June, reaches its maximum value in September, and gradually diminishes through October and November (Figure 1b). The purpose of this paper is to analyze the processes underlying the reduced warming and to show the hole's links to observed climate trends.

2. Methods

[4] Contemporary and scenario climate simulations by the Hadley Centre GCM Version 2 (HadCM2) [*Johns et al.*, 1997] provided boundary conditions, including sea surface temperature, for simulations using the RCM RegCM2 [*Giorgi et al.*, 1993]. HadCM2 was one of the two models for the U.S. National Assessment of Climate Change (U.S. Global Climate Change Research Program, Climate change impacts on the United States: The potential consequences of climate variability and change, http://www.usgcrp.gov/usgcrp/Library/nationalassessment/overview.htm, 2004), and RegCM2 is a widely used regional climate model. The spatial resolution of HadCM2 was 2.5° (latitude) × 3.75° (longitude) with 19 vertical levels. RegCM2 used 101 × 75 grid points centered at (100°W, 37.5°N) with a horizontal grid spacing of 52 km [*Pan et al.*, 2001b]. The resulting domain covered the continental U.S. and adjacent parts of Canada, Mexico, and neighboring oceans. Lateral boundary conditions obtained from HadCM2 were assimilated over a 15-grid wide forcing frame in RegCM2. The model in this study used 14 layers in the vertical, centered at σ = 0.995, 0.980, 0.950, 0.895, 0.815, 0.720, 0.615, 0.510, 0.405, 0.300, 0.210, 0.135, 0.070, and 0.020. The model top was located at 100 hPa. The HadCM2 scenario simulation assumed a 1% per year increase of effective greenhouse-gas concentrations after 1990.

[5] RegCM2 incorporates the surface model BATS Version 1e [*Dickinson et al.*, 1992], *Grell*'s [1993] simplified version of Arakawa-Schubert convection, and a simple

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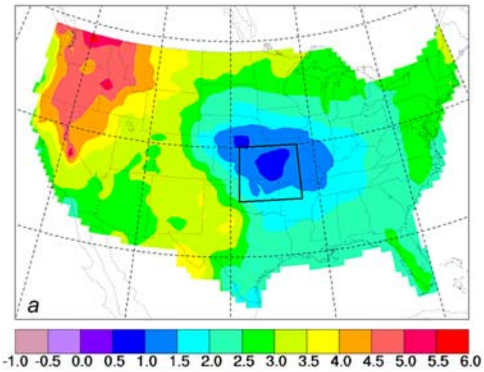

Figure 1a. Climate change in daily maximum temperature (K) in summer (June-July-August) simulated by RegCM2. The change is the difference between the future scenario decade (2040's) and current decade (1990's). Warming-hole averages in our analyses use the region delineated by the inner frame (35–40°N, 99–92°W).

warm-cloud physics, explicit-moisture scheme for resolved-scale precipitation. The BATS land surface scheme in RegCM2 has 18 categories of land use and 12 soil types with three overlapping soil layers: top layer (0.1 m), root zone (varies depending on land use type), and deep layer (10 m).

[6] The 10-year window used from HadCM2's control climate corresponds to the 1990's, while the window used for the climate projection is the decade 2040–2049 [*Pan et al.*, 2001b]. Model integrations were continuous for each of the ten-year periods although results are presented for the warm season only. We define "climate change" in the present report as the mean difference between these two decades.

3. Results

[7] The evolution and longevity of the warming hole are related to a distinctly mesoscale chain of feedbacks in the coupled atmosphere-land surface climate system. This feedback chain centers on the nocturnal southerly low-level jet (LLJ), a mesoscale dynamic feature that regulates moisture flow in the central U.S., and hence summertime precipitation [*Stensrud*, 1996]. LLJs are generated by a combination of large-scale orography (the slope from the Rocky Mountains to the Mississippi River) [*Fast and McCorcle*, 1990], diurnal variations in surface heating [*Blackadar*, 1957], and synoptic-scale dynamics [*Uccellini and Johnson*, 1979]. Convergence near the northern terminus of LLJs aids the release of conditional instability and organization of convection into coherent mesoscale convective systems [*Augustine and Caracena*, 1994]. Summer precipitation in the central U.S. has a nocturnal maximum, a unique feature that reflects the influence of LLJs and MCSs [*Fritsch et al.*, 1986]. Precipitation from MCSs accounts for roughly half of warm-season precipitation in the central U.S. [*Fritsch et al.*, 1986], and thus MCSs are critical to maintaining a reservoir of soil water for evapotranspiration. A change in precipitation that affects this moisture reservoir will alter soil-moisture feedback to atmospheric processes that influence climate.

[8] Our simulation for the current climate shows frequent LLJs in a swath from Texas to the north-central U.S., in agreement with observations [*Bonner*, 1968]. In the projected climate, LLJ occurrence increases to the south and decreases to the north of the warming hole region as indicated by the LLJ frequency change (Figure 2a). The increased frequency of LLJs in the southern U.S. is attributed in part to drier soil in Texas in the projected climate (Figure 2b), which enhances boundary layer processes that are conducive to LLJs [*Fast and McCorcle*, 1990; *Paegle et al.*, 1996]. Also, in the projected climate simulated precipitable water over the Gulf of Mexico (the main atmospheric moisture source for central U.S. precipitation in summer) increases by about 20%, reflecting Gulf

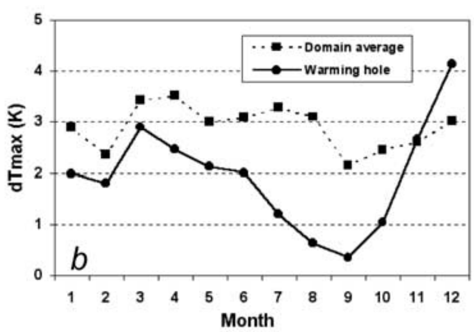

Figure 1b. Time series of change in monthly-mean daily maximum temperature (dT_{max}) averaged over the warming hole and for the land over the entire U.S.

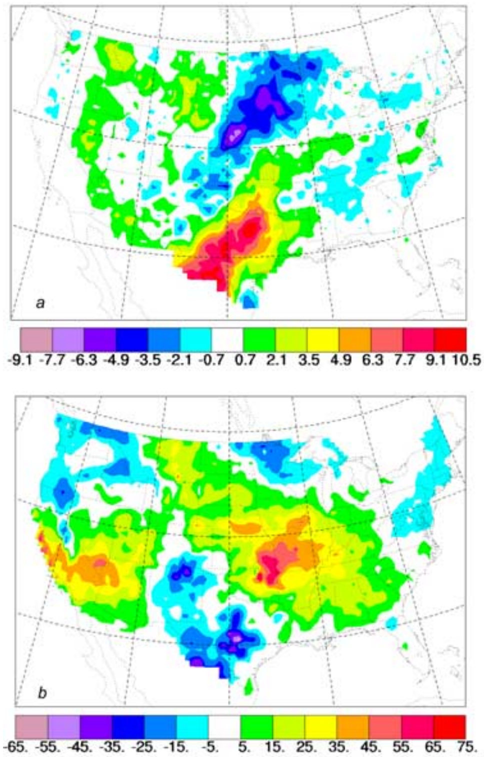

Figure 2. Climate change (2040's minus 1990's) in low-level jet frequency (%) at 06 UTC in summer (**a**) and change in root-zone soil moisture content in mm (**b**).

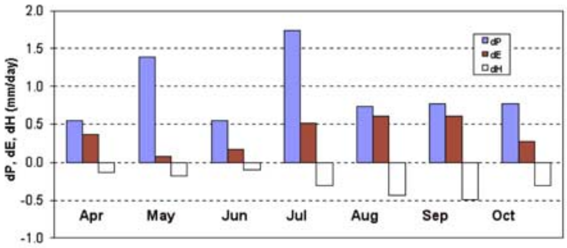

Figure 3. Warm-season monthly change in daily precipitation (dP), evapotranspiration (dE), and sensible heat flux (dH) in the warming hole delineated by the inner frame in Figure 1a.

of Mexico sea surface temperatures about 2 K warmer than in the current climate. These features promote low-level moisture convergence over the central U.S., which is favorable for the development of cloudiness and MCSs [*Anderson et al.*, 2003]. Increased low-level convergence at the gradient in LLJ frequency produces higher precipitation, particularly during May through July (Figure 3), which increases deep soil moisture. The mean summer precipitation increase in the warming hole area is about 1 mm d^{-1}. The increased cloudiness over the warming hole also reduces daily-average solar irradiance reaching the ground by about 8 Wm^{-2} [*Pan et al.*, 2004], thus reducing the direct surface warming and, equally important, inhibiting increased evapotranspiration during May and June (Figure 3) despite increased soil moistening. The result is that while both precipitation and evapotranspiration are higher in the projected climate, the increase in precipitation is greater than the increase in evapotranspiration in the region, so that soil moisture increases (Figure 2b). The resulting decrease in sensible heat flux (Figure 3) leads to suppression of atmospheric warming and thus formation of the warming hole. Increased evaporative cooling helps sustain the warming hole through October.

[9] Our results are consistent with observed decadal-scale trends of temperature and moisture over the central U.S. Observed global warming during the 20th century was characterized by two distinct warming periods (1910–1945 and 1976–2000), separated by a period with little change. During the latest warming (1976–2000), the central U.S. experienced a 0.2–0.8 K summer temperature decrease (Figure 4), one of the few major land regions to cool [*Folland et al.*, 2001]. The observed cooling center is somewhat northwest of the projected warming hole. The observed cooling may be partly attributable to irrigation on local scales; however, use of irrigation peaked during the early-1980s [*Segal et al.*, 1998] when irrigated area in the central U.S. reached about 60,000 km^2, much smaller than the extent of the observed warming hole. Our explanation for the warming hole based on regional simulations also is broadly consistent with other analyses that demonstrate the linkage between the observed cooling over the central U.S. and a long-term increase in precipitation in the same region [*Kalnay and Cai*, 2003; *Milly and Dunne*, 2001]. Thus a warming hole associated with increased precipitation has been emerging already in the central U.S., lending credibility to the model projection. Although we focus primarily on a regional perspective, remote forcing such as tropical sea surface temperature may also be responsible in part for east-central U.S. cooling in the second half of the twentieth century [*Robinson et al.*, 2002].

[10] The changing pattern of LLJ frequency and thus moisture convergence is the key to triggering the warming hole. One possibility is that LLJ occurrence is altered due to shifts in large-scale circulation systems in the scenario climate. Previous studies have shown that large-scale forcing (in combination with diurnal boundary-layer processes) often plays a role in formation of LLJs [*Uccellini and Johnson*, 1979], so that changes in upper-level flow patterns will affect the frequency and strength of the LLJs. We diagnosed observed trends in winds at 850 hPa (close to the average height of LLJs over the western Great Plains) for 1979–1998 and found a spatial structure and trend resembling our projections for the future scenario climate (increased southerly winds in the south-central U.S. and decreased southerly winds in the north-central U.S.), implying increased convergence in the central U.S. We also found that changes in mean 500 hPa height and sea-level pressure fields for the scenario climate during summer show enhanced troughing from Lake Superior to the Texas panhandle (not shown); climatological studies indicate that such a pattern tends to produce stronger and more frequent LLJs and in turn increases precipitation [*Arritt et al.*, 1997].

4. Conclusions

[11] We have examined a discrepancy between observed temperature trends over the central U.S. and GCM projections by using a regional climate model with finer resolution than current global models. We found a local minimum of warming in the central U.S. that is associated with a linkage between changes in atmospheric circulation (incidence of the Great Plains LLJ), soil moisture, and the surface energy balance. In a simulation of an enhanced greenhouse-gas scenario, LLJs occurred with higher frequency in the south-central U.S. and with lower frequency in the north-central U.S. from May through July (Figure 2a). Greater moisture convergence implied by the north-south gradient in changes of LLJ frequency produced increased precipitation from May through July in the projected climate, which in turn led to increased summer soil moisture, enhanced evapotranspiration, and reduced surface warming during July to

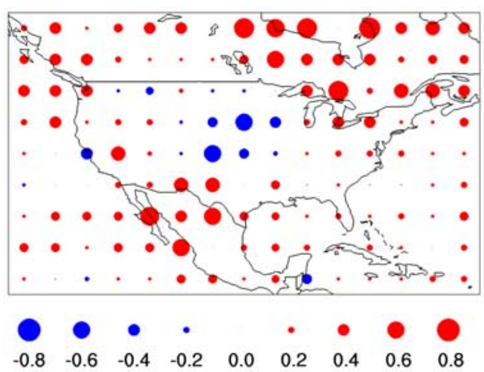

Figure 4. Observed summer (June-July-August) daily mean temperature changes (K) between 1976–2000 (Based on *Folland et al.* [2001]).

October compared to surrounding regions. We emphasize the role of the soil moisture reservoir in providing additional "climate memory" that extends the regional reduction in warming beyond the period of increased precipitation.

[12] In light of the feedback process described herein we conclude that in order to produce accurate projections of changes in the climate of the central U.S. it is necessary to simulate the mesoscale processes that convert converged moisture into rainfall near the northern terminus of southerly LLJs [*Augustine and Caracena*, 1994]. Regional climate models simulate these processes reasonably well judging from the Project to Intercompare Regional Climate Simulations (PIRCS) experiments, which evaluated 16 such models [*Anderson et al.*, 2003], and our previous studies [*Pan et al.*, 2000]. In contrast current global climate models (GCMs) poorly simulate the link between regional precipitation and LLJs, due in part to their coarse spatial resolution [*Ghan et al.*, 1996]. Thus, climate change studies using GCMs with typical horizontal node spacing of 200–300 km cannot resolve the mesoscale processes that play key roles in the central U.S. summer climate. This may explain why most GCMs do not include the warming hole. Finally we caution that although our results are broadly consistent with observed trends, additional multiyear simulations should be performed using other regional models and other GCMs and greenhouse-gas emission scenarios in order to determine the robustness of our findings.

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